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Surface-mode lasing from optically pumped InGaN/GaN heterostructures

A. V. Sakharov, W. V. Lundin, V. A. Semenov, A. S. Usikov, N. N. Ledentsov, A. F. Tsatsul'nikov, Zh. I. Alferov, A. Hoffmann† and D. Bimberg†
Ioffe Physico-Technical Institute, St Petersburg, Russia
† Institute für Festkörperphysik, Technische Universität Berlin, Hardenbergstr. 36, D-10623 Berlin, Germany

Devices based on III-nitride compound semiconductors have been rapidly and successfully developed in recent years as highly efficient emitters of visible light. Long-lived blue laser diodes [1] along with high brightness blue, green, and most recently, amber light emitting diodes have been demonstrated. GaN-based surface emitting lasers have attracted wide attention because of naturally integrated mirrors, low beam divergence and possibilities to fabricate dense two-dimensional arrays of short-wavelength semiconductor lasers important for high-density high-speed optical storage applications. At the same time, fabrication of such devices was thought to be very complicated in view of the necessity to epitaxially grow conductive and highly reflective quarter wave Bragg mirrors based on GaN/AlGaN materials.

On the other hand, it was demonstrated, that ultrahigh modal gain in structures with stacked dense arrays of wide-gap II–VI quantum dots (QDs) allows to realize ultrahigh gain coefficients and achieve surface lasing even without using of Bragg reflectors [2]. It was shown also, that ultrathin InGaN deposits result in spontaneous formation of dense arrays of nanoislands [3]. Moreover, spontaneous spinodal decomposition of the InGaN alloys also favors formation of QD-like structures [4, 5]. Indeed, high modal gain in 0.1 μm-thick InGaN layers at high excitation densities allowed some authors [6, 7] to observe stimulated emission in vertical direction. At the same time no evidence of the importance of the feedback in the system resulting in appearance of lasing modes was given. In this work we fabricated and study optical properties of the structure composed of closely packed stacks of ultrathin InGaN insertions. We demonstrate possibility to achieve ultrahigh material gain in the system and achieve surface lasing. Characteristic typical for QD lasers temperature dependence of threshold excitation density and gain-spectrum — cavity mode self-adjustment effects are observed.

The samples used in this work were grown on (0001)-oriented sapphire substrates by low pressure metalorganic chemical vapour deposition technique and employing an AlGaN nucleation layer deposited at 530 °C [8]. Ammonia, trimethylindium (TMI), trimethylgallium (TMG) and thrimethylaluminum (TMA) were applied as component precursors. Purified hydrogen and argon were used as carrier gases. Argon was used as a bubbling gas for TMI while hydrogen was used as a bubbling gas for TMG and TMA. Samples consist of a 2.5 μm GaN layer deposited at 1050 °C at pressure 200 mbar using H_2 as carrier gas, a InGaN/GaN active region formed by temperature cycling at 600 mbar pressure using Ar as carrier gas, and a 0.1 μm GaN cap layer deposited at 1050 °C. Active region consisted of thin (25 nm) intermediate InGaN layer with low indium composition (8%) deposited at 800 °C followed by superlattice composed of 12 periods. The superlattice is formed due to temperature cycling from 730 to 860 °C, resulting in a strongly modulated In compositional profile, as In incorporates only at low temperatures. During the growth of the active region

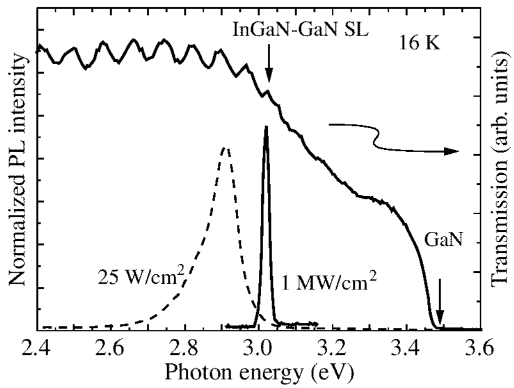

Fig. 1. Low temperature PL spectra at low excitation density, surface lasing and transmission spectra of structure under study.

TMI and TMG flows were constant. It was shown [3–5] that low temperature growth of InGaN leads to formation of dense array of In-rich nanoclasters (quantum dots).

The period of the superlattice obtained from XRD data was 12 nm, that in a good agreement with value estimated from the TMG flow. Average In content in the active region obtained from XRD was 8%. The width of the InGaN insertion estimated from temperature monitoring is about 4 nm. Photoluminescence (PL) measurements were performed in the temperature range 16–300 K by using close-cycle He cryostat. The samples were excited by He-Cd laser (325 nm, 25 mW) or by pulsed N_2 laser (337.1 nm, 1.5 kW). The laser beam was focused into a spot with a diameter of 400 μm. The laser light intensity was attenuated using a set of neutral density filters. The emission was coupled into MDR-23 spectrometer and detected by cooled photomultiplyer.

The low-temperature photoluminescence, surface lasing and optical transmission spectra are shown in Fig. 1. The PL spectrum shows a single peak with tails exhibiting near exponential behavior on both high and low energy side. A significant energy shift between PL maximum and the onset of the InGaN absorption in the transmission spectra strongly support formation of In-rich nanodomains. At large excitation densities, PL emission narrows and its intensity strongly increases. The PL maximum intensity shifts to the high energy side of the luminescence band at low excitation density, but still remains on the low energy side with respect to the onset of the InGaN-GaN SL-induced absorption.

The dependence of PL intensity on excitation density at 150 K is shown in Fig. 2(a). PL spectra for different excitation density are shown in Fig. 2(b). It can be seen that in all the spectra the PL is modulated by Fabry–Perrot microcavity modes formed by GaN/Al_2O_3 interface and GaN surface. It is clearly seen that at high excitation densities ($>$ 600 kW/cm^2) one of the resonator modes starts to dominate in the PL spectra and its peak intensity grows superlinearly. Single-mode emission together with strong increase in the slope efficiency indicate the presence of the feedback in this system despite of the remarkably low finesse of the cavity. To the best of our knowledge, it is the first demonstration of lasing in vertical direction for structures with quantum-size InGaN/GaN insertions.

We also note that stimulated emission in edge direction was observed at excitation densities of about one order of magnitude lower than those for vertical lasing. Simultaneously with appearance of a narrow line in edge geometry we observed saturation of spontaneous recombination. Thus for vertical lasing, stimulated emission in edge geometry may play a

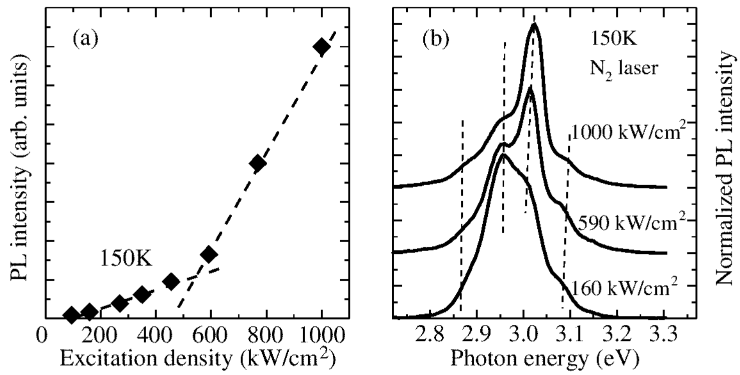

Fig. 2. Photoluminescense intensity *versus* excitation density (*a*) and PL spectra (*b*) taken at 150 K.

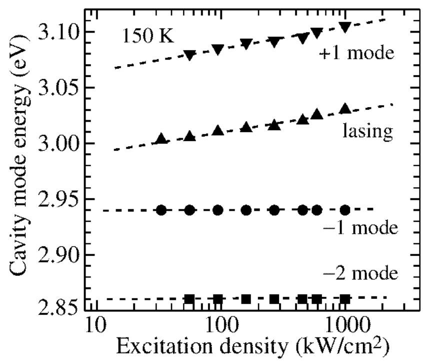

Fig. 3. Cavity modes position of Fabry–Perrot cavity versus excitation density.

negative role.

The threshold gain necessary to achieve surface lasing (g_{th}) can be written as:

$$g_{\text{th}} = \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$$

where R_1 and R_2 are reflectivity coefficients of both interfaces forming the cavity, and L the cavity length. We can neglected internal losses in GaN in this case. We estimate the reflectivity coefficients to be 2.4% for GaN/Al_2O_3 and 17% for GaN/air interfaces using the refractive indexes of unity for air, 2.4 for GaN, and 1.75 for sapphire. Then, taking into account that the active region, resulting in gain, has a thickness of 0.15 μm, we obtain the value of 2×10^5 cm^{-1} for the threshold gain.

In addition we observe short-wavelength shift of the cavity modes with increase in the excitation density (see Fig. 2(b)). The largest shift (2.6 nm) was observed for the high-energy modes, while the low energy modes does not shift. This effect can be described via Kramers–Kroning equations, and can be explained by a strong modulation of the absorption/gain curve in the vicinity of the lasing energy.

Figure 3 demonstrates the dependence of cavity modes on excitation density for a broader range of excitation densities. The effect of interaction of gain spectrum and cavity modes is characteristic for QD vertical cavity lasers surface emitting lasers and was reported for injection lasers based on InGaAs/GaAs quantum dots [9], and II–VI QD structures under photoexcitation.

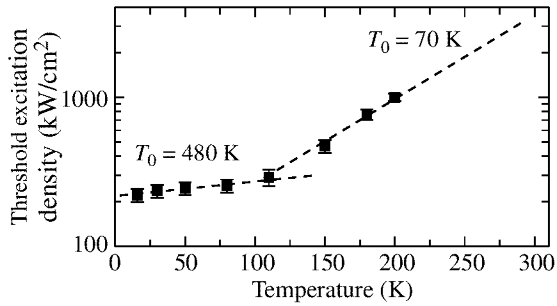

Fig. 4. Temperature dependence of threshold excitation density.

Temperature dependence of the threshold excitation density for vertical lasing is shown in Fig. 4. In a temperature range between 16 and 120 K the threshold excitation density remains weakly affected, while it increases at higher temperatures. The temperature dependence can be extrapolated in two ranges via empirical equation:

$$P_{\text{th}} = P_0 \times \exp\left(\frac{T}{T_0}\right)$$

with $T_0 = 480$ K in the low temperature range and $T_0 = 70$ K in the high temperature range. Similar temperature dependencies was reported for InGaAs-GaAs quantum dot lasers [9]. Increasing of the threshold excitation density at higher temperatures can be explained by thermal evaporation of carriers from QDs [10].

To conclude we have demonstrated vertical lasing without Bragg reflectors in structure with multiple InGaN/GaN insertions. Laser action is confirmed by superlinear dependence of the output intensity versus excitation density and by appearance of a single lasing mode defined by a vertical Fabry–Perrot cavity formed by GaN/air and GaN/Al_2O_3 interfaces. Effect of interaction of gain spectrum and cavity modes is demonstrated.

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References

[1] S. Nakamura, *et al.*, *Appl. Phys. Lett.* **72**, 2014 (1998).
[2] I. L. Krestnikov, *et al.*, *Phys. Rev. B in print* (1999).
[3] K. Tachibana, *et al.*, *Appl. Phys. Lett.* **74**, 383 (1999).
[4] S. Nakamura, *et al.*, *Appl. Phys. Lett.* **70**, 2753 (1997).
[5] A. Vertikov, *et al.*, *Appl. Phys. Lett.* **73**, 493 (1998);
K. Tachibana, *et al.*, *Appl. Phys. Lett.* **74**, 383 (1999);
R. W. Martin, *et al.*, *Appl. Phys. Lett.* **74**, 263 (1999).
[6] S. T. Kim, H. Amano, I. Akasaki, *Appl. Phys. Lett.* **67**, 267 (1995).
[7] M. Asif Khan, *et al.*, *Appl. Phys. Lett.* **65**, 520 (1994).
[8] J. Christen, *et al.*, Physica E **2**, 557 (1998).
[9] N. N. Ledentsov, *et al.*, *Semicond. Sci. Technol.* **13**, 99 (1999).
[10] N. Kirstaedter, *et al.*, *Electron. Lett.* **30**, 1416 (1994).